

A Senior Thesis

**Refined Estimates of the Depths of Magma Chambers Beneath the
Reykjanes and Kolbeinsey Ridges, and Implications for the
Structure of Oceanic Crust**

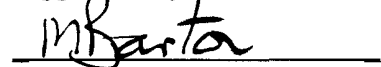
By

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A handwritten signature in black ink, appearing to read "M. Barton", is written over a horizontal line.

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Abstract

The mid-Atlantic ridge is the divergent plate boundary between North and South America to the west and Europe and Africa to the east. Plate separation is accompanied by intrusion of dikes and eruption of lava along the ridge axis. The dikes are fed by magma chamber(s) located beneath the ridge and it has been suggested that the depth of magma chambers is related to the rate of spreading. In order to test this hypothesis we determined the depths of magma chambers beneath the slow spreading Reykjanes Ridge that extends from the Charlie Gibbs fracture zone at 53° north to the southern tip of Iceland at 64° north and the Kolbeinsey Ridge that extends from north of Iceland at about 66 degrees north to the west Jan Mayan ridge at about 71 degrees north in the North Atlantic. Pressures of partial crystallization were calculated from comparison the compositions of natural liquids (glasses) with those of experimental liquids in equilibrium with olivine, plagioclase, and clinopyroxene at different pressures and temperature. Chemical analyses of mid-ocean ridge basalts (MORB) glasses collected along the Reykjanes and Kolbeinsey Ridge were used as liquid compositions. The glasses form by rapid cooling of magma when quenched by contact with seawater, and provide unambiguous samples of natural basalt liquids. The calculated pressures were used to estimate the depths of partial crystallization of the host magmas in sub-crustal chambers or reservoirs. The results indicate that the depth of magma chambers of the Reykjanes Ridge decreases from 4 - 8 km (± 0.8 km) near the Charlie Gibbs fracture zone to 1.2 ± 0.5 km at 55.67° N. As the Ridge approaches Iceland the depth of chambers increases to 9.7 ± 3 km. The limited data available for the Kolbeinsey Ridge provides only an approximate estimate of the depth of magma chambers (average, 8.2 km) but the depths also seem to increase towards Iceland.. The shallow depths obtained for chambers beneath the southern part of the Reykjanes ridge and the average depth of chambers beneath the Kolbeinsey

ridge is in contrast with results obtained for slow-spreading ridges elsewhere. This may reflect increased magma flux associated with the Iceland plume, and this is consistent with crustal thickening towards Iceland as suggested by the northerly increase in the maximum depths of chambers along the Reykjanus ridge. . The influence of the Iceland plume is apparent from the chemical analyses of the glasses. The abundances of Ti, Na, K, P, and Fe increase whereas the abundances of Si, Mg, Al, and Ca decrease as Iceland is approached. These chemical data can be interpreted in terms of increased magma flux reflecting the thermal effects of the Iceland plume.

Introduction

Most of the world's magmatic events and crustal growth occurs at Mid-Ocean Ridges (MOR)(Pan et al 2003). Because the MORs are located under the oceans these processes are relatively poorly understood, and many questions remain to be answered; for example how is the crust accreted, and what does the crust's thermal structure at the ridges look like. Two models have been presented to describe crustal accretion. The first of these is termed the gabbro glacier model. In this model there is a shallow melt lens that feed eruptions and in which crystals form in magmas differentiate. These crystals form gabbros that slide down and away from the melt lens like a glacier moves down a mountain. The second of these models is referred to as the many sills model. In this model the melts and crystals form a mush with many different melt lenses that form sills though-out the entire gabbro complex in the middle and lower crust (MacLennan et al 2004). New crust is created by crystallization of the magma but the melt able to move quickly from sill to sill.

The thermal structure of the crust has been suggested to be related to both the spreading rate and magma flux of a ridge segment. Warm crust is associated with few fractures zones, fast

spreading rates, and high magma flux; whereas cold crust has more fractures zones, slower spreading rates, and low magma flux (Herzberg 2004).

There is an apparent relationship between spreading rate and depth of the magma chambers. The ridges with fast spreading rates are thought to have shallow (mid to near surface depths) magma chambers. The slow spreading ridges are thought to have the magma chambers near the base of the crust and in the underlying upper the mantle (Herzberg, 2004). This is reflects the fact that at fast spreading ridges the increase magma flux increases the temperature of the crust allowing the magma to reach higher levels before the onset of partial crystallization than in colder, lower flux, slow spreading ridges. An important exception to this rule is the Reykjanes Ridge just south of Iceland. The Reykjanes Ridge is a slow spreading ridge but appears to have magma chambers at shallow depths. The low pressure of crystallization is thought to be caused by a mantle plume that adds extra heat to the ridge and is centered beneath Iceland. The more northern Kolbeinsey Ridge, which due to proximity to Iceland should show results similar to the Reykjanes Ridge.

This study has three main objectives. The first is to establish in detail the depth of the magma chambers beneath the Raykjanes and Kolbeinsey Ridges. The second is to study the variation of chambers depths as a function of distance from Iceland (the plume or heat source). The third is to use the crystallization depth to infer crustal thickness along the ridges as a function of distance from Iceland. The rationale for this is as the magma ascends from the mantle it should pond in areas of density contrast, one of the most important of which is at the mantle transition (MOHO) to the crust.

Geologic Background

The area of study for this paper is the Reykjanes and Kolbeinsey ridges. These ridges belong to the Mid-Atlantic ridge (MAR) system and are separated from each other by Iceland (figure 1). The Reykjanes, Iceland, and Kolbeinsey system is marked by a large scale bathymetric anomaly that is centered on Iceland and raises the sea floor by 2 to 3 km higher than other similarly aged oceanic crust (Foulger et al. 2005). The Reykjanes Ridge is the ~1000 Km segment defined by the Charlie Gibbs Fracture Zone to the south at 53°N to where it becomes sub-aerial on the Reykjanes Peninsula at about 64°N. The sea floor depth along this area ranges from 7 Km in the south to 0 where it meets Iceland. The Reykjanes Ridge has a half spreading rate of about 10 mm a year (Luyendyk et al). This spreading direction is oblique to ridge at between 28° to 30° (off orthogonal) (van Wijk et al 2007). The Reykjanes Ridge does not have the typical well-defined rift valley as seen at other slow-spreading ridges. The ridge crest is about 50 Km wide and 1 Km high (Luyendyk et al). The ridge crest there are en echelon magmatic segments. The midpoints of these segments strike close to orthogonal to the plate spreading direction and their tips are rotated counter-clockwise and overlap (van Wijk et al 2007). The Reykjanes Ridge is characterized by southward pointing V-shaped ridges (Foulger et al. 2005) that run for hundreds of kilometers lacks off-setting fracture zones. The absence of fracture makes the Reykjanes distinct from the rest of the MAR as the MAR is typically off-set by fracture zones at about 50 Km intervals (Luyendyk et al).

The Kolbeinsey Ridge is the ~540 Km segment that runs north of Iceland from the Tjornes Fracture Zone at about 66.5°N to the Jan Mayan Fracture Zone at about 71°N. The Tjornes Fracture Zone offsets the Kolbeinsey Ridge from the active volcanic rift in Iceland, and the Jan Mayan Fracture Zone separates the ridge from the Mohns Ridge to the north (Devey et al

1994). The sea floor depth is about 1 km on average but is shallower closer to Iceland and drops below 2 Km as it approaches the Jan Mayan Fracture Zone. The ridge has a half spreading rate of 10 mm a year. The Kolbeinsey Ridge is divided into three segments known as the South Kolbeinsey (SKR), Mid Kolbeinsey (MKR) and North Kolbeinsey (NKR). The SKR is similar to the Reykjanes as it has no well-defined rift valley whereas both the MKR and NKR have the rift valley common to slow spreading ridges. (Haase et al 2003).

Method

Many basalt magmas crystallize olivine (ol) ($(\text{Mg, Fe})_2\text{SiO}_4$), plagioclase (plag) ($(\text{Ca, Na})(\text{Al}_{2-1}\text{Si}_{2-3})\text{O}_8$), and clinopyroxene (cpx) ($\text{Ca}(\text{Mg, Fe}^{2+})\text{Si}_2\text{O}_6$). Experiments have established the composition of liquids in equilibrium with these three minerals as a function of pressures at different pressures. The liquid compositions produced from both individual and multiple samples at a given pressure define the position of cotectic for that pressure along which the melts are in equilibrium with ol, plag, cpx. These cotectics are projected from plag onto the plane ol-cpx-qtz using the recalculation procedure of Walker et al (1979) in figure 2. This clearly shows the shift of the ol-plag-cpx cotectic towards ol with increasing P (figure 2). The compositions of natural samples can be plotted and compared with these cotectics to obtain a qualitative estimate of pressures.

Yang et al. (1996) presented three equations that allow direct calculation of liquid composition lying along the cotectics. These equations can be used to calculate a series of liquid compositions (LP) lying along the ol-plag-cpx cotectic for the sample of interest at increments of 100MPa. The liquid compositions are converted to normative mineral components using the procedure described by Grove et al. (1993). The pressure dependence of each normative mineral

component in the predicted liquids (LP) is found by regression, and the pressure of crystallization is found from the regression equations using the projected normative mineral components for the original sample (LS). Thus for the projection from plag, values of P are calculated from predicted and observed ol, cpx and qtz, whereas for the projection from ol, values of P are calculated from predicted and observed plag, cpx and qtz. We have used these two projections because most basalt melts are saturated with plag and ol, and obtain six values of P for each sample. The average value is taken as the pressure of crystallization, and all values are used to calculate the uncertainty (1σ) associated with the calculated pressure.

Treatment of data

Analyses of MORB glasses from the Reykjanes and Kolbeinsey Ridges were retrieved from www.petdb.org a database of petrologic data. First all of the major oxide data was plotted versus latitude to determine the chemical variations over the entire length of each ridge. The analyses of the Reykjanes glasses were examined first. A total of 864 samples were retrieved from the database for this ridge and where appropriate any Fe_2O_3 was converted to FeO, so that Fe is reported as ΣFeO . Secondly variations of Al_2O_3 , CaO, and $\text{CaO}/\text{Al}_2\text{O}_3$ with MgO examined for the entire data set (figure 3) to make sure that the melts were in equilibrium with ol, plag, and cpx.

The plots of Al_2O_3 , CaO, and $\text{CaO}/\text{Al}_2\text{O}_3$ versus MgO were used to identify those glasses that represent melts in equilibrium with ol, plag, and cpx. To be consistent with a melt that is at equilibrium with ol, plag, and cpx the Al_2O_3 and CaO trends must decrease with a decrease in MgO and the $\text{CaO}/\text{Al}_2\text{O}_3$ must remain constant or decrease very slightly. Samples that were not on the trend that is consistent for equilibrium with ol, plag, and cpx were filtered out of the sub

sets. The data set was also divided into subgroups by latitude and the data for each subgroup was examined to identify liquid in equilibrium with ol, plag, and cpx.

The pressures were calculated using an Excel spreadsheet that was described by Kelly et al. (2008). Any negative results (clearly unrealistic and probably the result of analytical errors) were not considered. The final number of samples after all of the filtering was 656. The pressures for these samples were then plotted versus latitude (figure 4). Results for clusters of samples that were separated by less than 0.03 degree of latitude (or about 3.34 Km), were combined as they are likely to indicate the presence of a single magma chamber. In all, magma chambers were identified at 20 locations. For convenience, the results for each specific locality were averaged, and uncertainties were calculated at one standard deviation about the average. Pressures were converted to depth assuming a crustal density of 2900 kg m^{-3} (i.e. a typical value for basalts).

There only 24 glass samples in the database for the Kolbeinsey Ridge. Due to the small number of samples the Kolbeinsey ridges data was treated differently. All of the samples were ran though the Excel spreadsheet. Any negative pressures were again not considered. When plotted versus latitude there are no more than three data points per location. Because of this, the decision was made to take average of all of the results. The location for the placement of the data point on the map was the average latitude for the data. The uncertainties and conversion of pressure to depth are the same as for the Reykjanes data.

A measure of the thickness of the crust along these ridges is needed so we could determine if partial crystallization occurs in the deep crust or in the shallow crust. At mid-ocean ridges the magma that is supplies in the chambers comes for the melting of the mantle. As this melt rises to the crust logic dictates that some of it would first pool at the base of the crust and

start to crystallize there. This is because of the density contrast at the MOHO between the crust and the mantle. At each location the maximum depth was taken as a possible indication of the base of the crust if that depth was outside of one standard deviation from the average depth. These maximum depths were compared with crustal thickness estimates based on seismic data (figure 5) (Folgers 2005).

Results

Most samples used were olivine tholeiites that follow a strong iron enrichment trend (plot of FeO versus MgO) with little enrichment in SiO₂. Of the 20 locations for the Reykjanes ridge only 5 were located in the southern half of the ridge (south of ~58°N). This area was dominated by fractures. The remaining 15 were located in the area of the ridge that is unfractured and show V-shaped ridges. The average depth of magma chambers for the entire ridge was 6.05 Km with all but one being <11 Km. The depth of magma chambers for these locations differ from results obtained by other workers for slow spreading ridges elsewhere along the ridge system. At two locations, uncertainties in the pressure indicate there could be magma chambers within ~1 km of the sea-floor (figure 6).

There is a decrease in average depth of partial crystallization from 53°N to ~55°N, then an increase in average depth from 62°N to 64°N, that is, towards Iceland. The average depth remains approximately constant at about 5 km between ~55°N and 62°N. The crustal thickness shown by a second degree polynomial regression show a trend that follows that of the average depth partial crystallization decreasing from the Charlie Gibbs fracture zone to 56°N then increase as Iceland is approached (figure 6). The average depth for the Kolbeinsey was 8.05 ±6.34. Because of the wide range of depths from the ridge we simplified the comparison with the

crustal thickness of the average latitude and one standard deviation to that. The average does not change but the standard deviation for depth is reduced to 3.36 Km. The crustal thickness for this location is about 12.8Km.

Discussion

The result of this study has confirmed the abnormally low pressures of partial crystallization for the slow spreading Reykjanes Ridge. As hinted at in the introduction there is thought to be a mantle plume beneath Iceland that may be causing the anomalous behavior of these ridges. I believe that the Icelandic Plume, as it is known, is interacting with the Reykjanes and Kolbeinsey Ridges. I examined the geochemical data used in this study to see if this lends support to this theory. As stated earlier because of the lack of data from the Kolbeinsey Ridge, data for the Reykjanes Ridge was used. To provide evidence for a mantle plume an increase in thermal structure and magma flux was sought as Iceland is approached. Then variations in incompatible elements changes abundances can be compared with changes in the previous two factors.

To look at the melt or thermal variation on the ridge we used $Na_{8.0}$. $Na_{8.0}$ is the weight percentage of Na_2O corrected for fractionation to 8% MgO (Michael et al 1998). To calculate this we used the methods described in Michael et al (1998). The use of $Na_{8.0}$ can tell us two things; the first is the extent of melting beneath the ridge and the second is crustal thickness (Michael et al 1998). As $Na_{8.0}$ decreases, both the amount of melting and the thickness of the crust increase. The changes in the amount of melting can be used as a proxy for variation in the thermal state of the mantle beneath the ridge. By the same token, crustal thickness is often used to as a proxy for the magma flux (Foulger et al 2005.) As Iceland is approached the $Na_{8.0}$ decreases (figure 7) this

indicates that as Iceland is approached the Reykjanes Ridge is getting warmer and, as confirmed with seismic and petrologic data, the crust is getting thicker.

The expected behavior of the incompatible elements with respect to the increased degrees of melting, if the mantle beneath Iceland is homogenous, is to decrease in abundance. This is not what happens (figure 7). What we see is a change from a more MORB like composition at the southern end to an Oceanic Island Basalt (OIB) composition near Iceland (Schilling 1973). The OIB are thought to come from a mantle plume source. In Schilling (1973) it is stated that the best model to meet all the requirements for what is happening along the ridge is a mantle plume mixing model. Unfortunately for this study I did not have the isotope data that would be a better indicator for change from MORB to OIB.

Another result of this study was to lend support for the many sills model at least along the Reykjanes. This conclusion is based on an examination of the correlation between MgO and the pressure. If the MgO changes at a near constant pressure then this would indicate crystallization in a magma chamber at that pressure. If the gabbro glacier model was occurring along these ridges then most samples would yield similar values of pressure at variable concentrations of MgO. The expected result for a crust with many sills would be either multiple pressures for magma crystallization at a single locality or no clear evidence for discrete magma chambers (MacLennan et al 2004). The results for different Reykjanes locations favored the latter scenario (figure 8). Published studies, also lend support to this conclusion. Pan et al 2002 showed that the residence time for magma in MOR chambers is 30-90 days, and noted that the short residence time favors the many sills model over the gabbro glacier model. In addition is the crystal structure of similar MORB also supports the many sills model. Plagioclase forms rigid

crystal networks in these rocks, which have been interpreted as coming from a mushy zone in magma chambers (Pan et al 2003).

Conclusion

The results of this study have lead to six main conclusions. Frist, while the results for Reykjanes and Kolbeinsey Ridges show that these ridges do not behave as typical slow spreading ridges, the results do support the conclusion of earlier workers that magma intruded along these ridges partially crystallize at low pressures. Second, along these mid-ocean ridge segments the maximum depth of crystallization can be used to estimate the depth to the base of the crust. Third, the crust thickens as Iceland is approached. Fourth, the mantle beneath Iceland is thermal and compositionally anomalous, which may be due to the presence of a mantle plume beneath Iceland. Fifth, this anomalous mantle is moving down and mixing with the mantle beneath the Reykjanes Ridge. Finally, it seems that crustal accretion along the Reykjanes Ridge is better explained by the many stills model than by the gabbro glacier model.

Figures

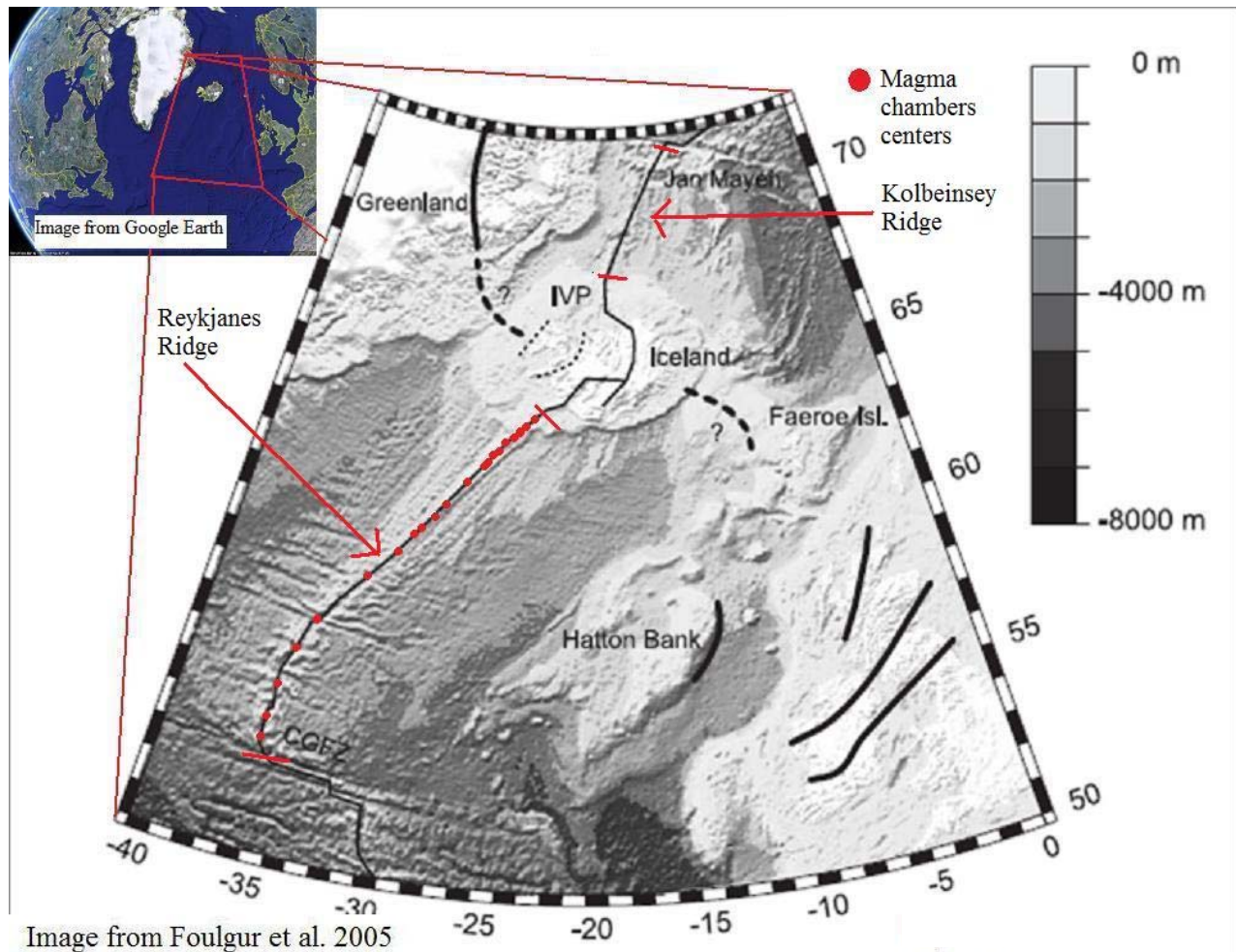


Figure 1: The Reykjanes Ridge extends from the Charlie Gibbs Fracture Zone (CGI). The Kolbeinsey Ridge extends from Iceland to the Jan Mayer Transform. Both ridges occur between the red lines while magma chambers along the Reykjanes are represented by red circles.

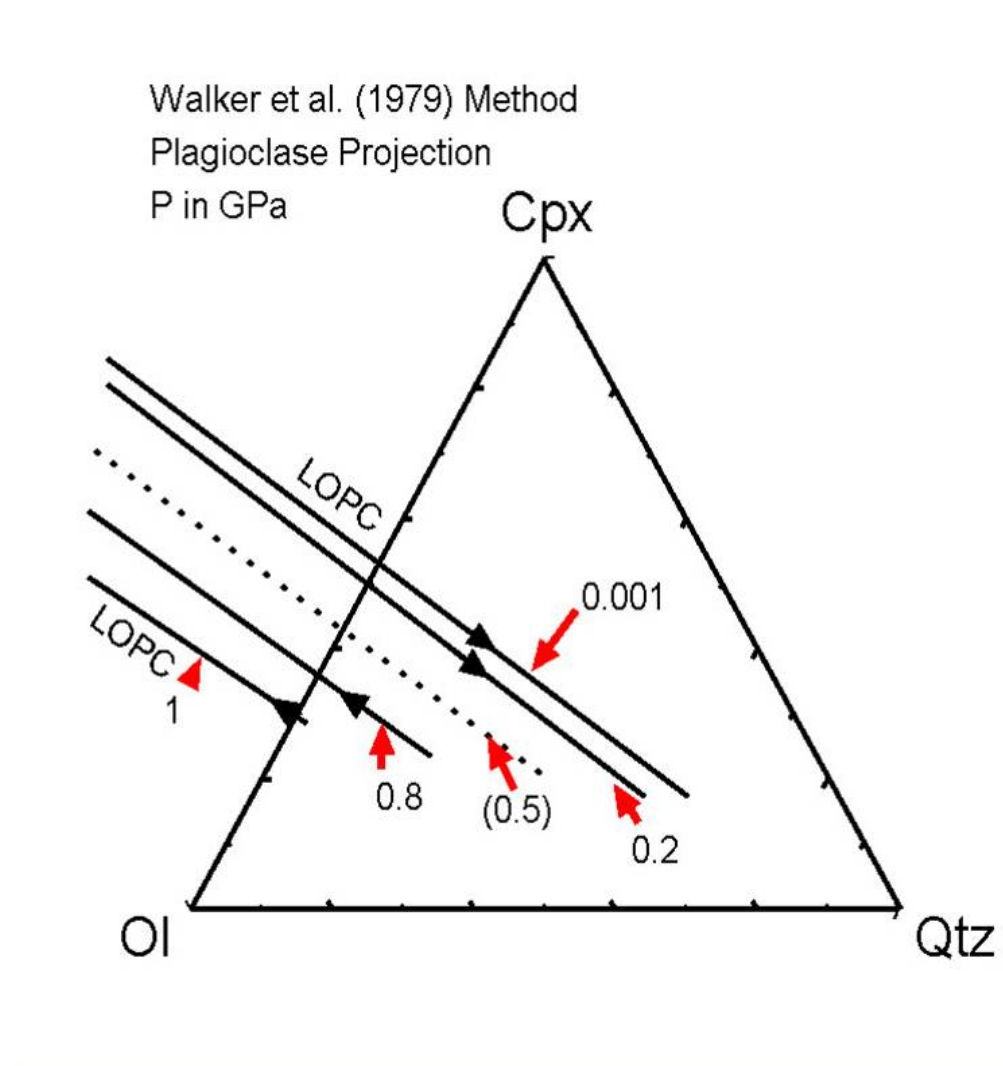


Figure 2: Graph from Walker et al 1979 show the evolution of a melt as it crystallizes along a cotectic at each given pressure.

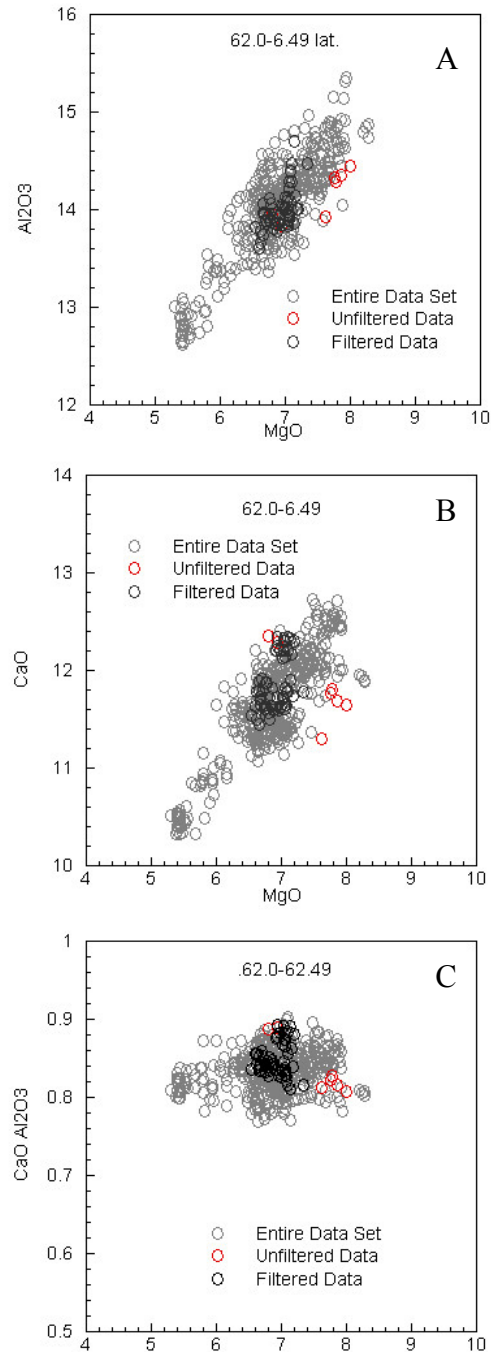


Figure 3: Al₂O₃ (Graph A) and CaO (Graph B) plotted vs. MgO concentration showing a positive correlation between the chemical species. **Grey** - entire dataset, **Red** - data that does not fit general trend, **Black** - data used in these analyses

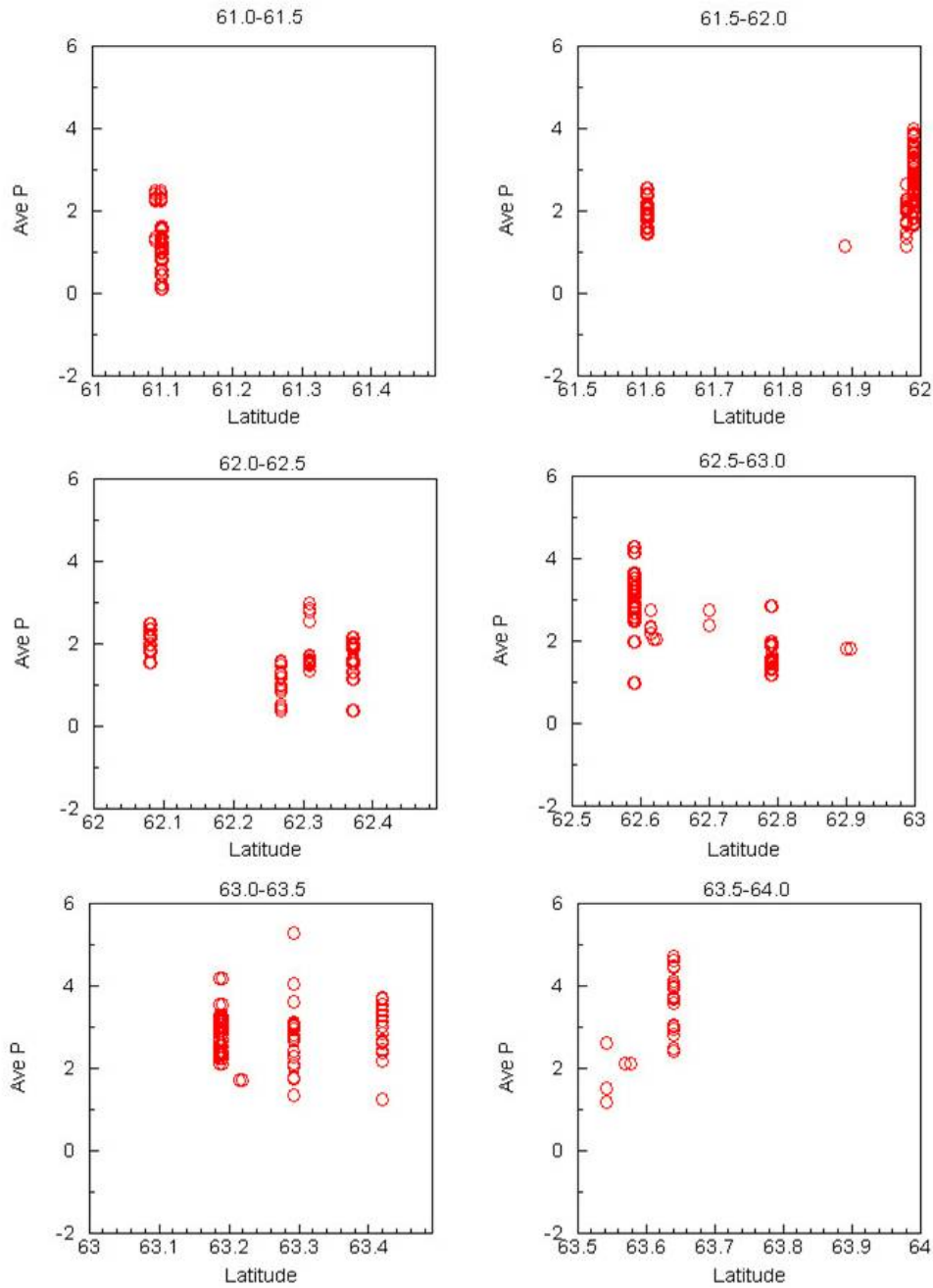


Figure 4: the entire data set pressure vs. latitude form 61.0 to 64.0 °N

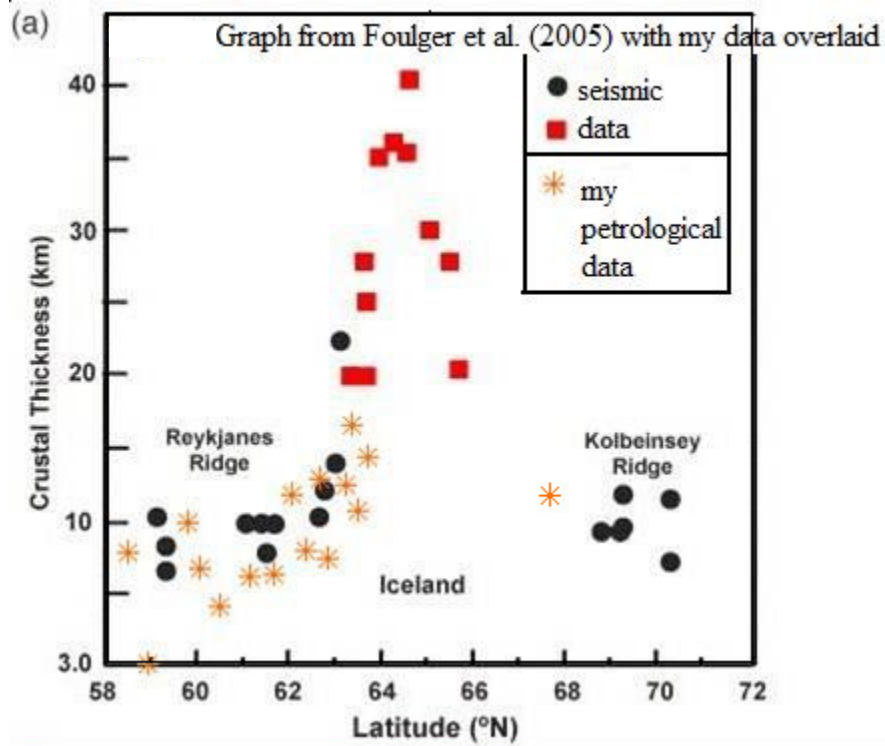


Figure 5: Petrologic data compared to seismic data of the area. The black circles and the red squares are seismic data and the orange stars are the maximum depths. This shows that the maximum depths for the data correspond to the base of the crust.

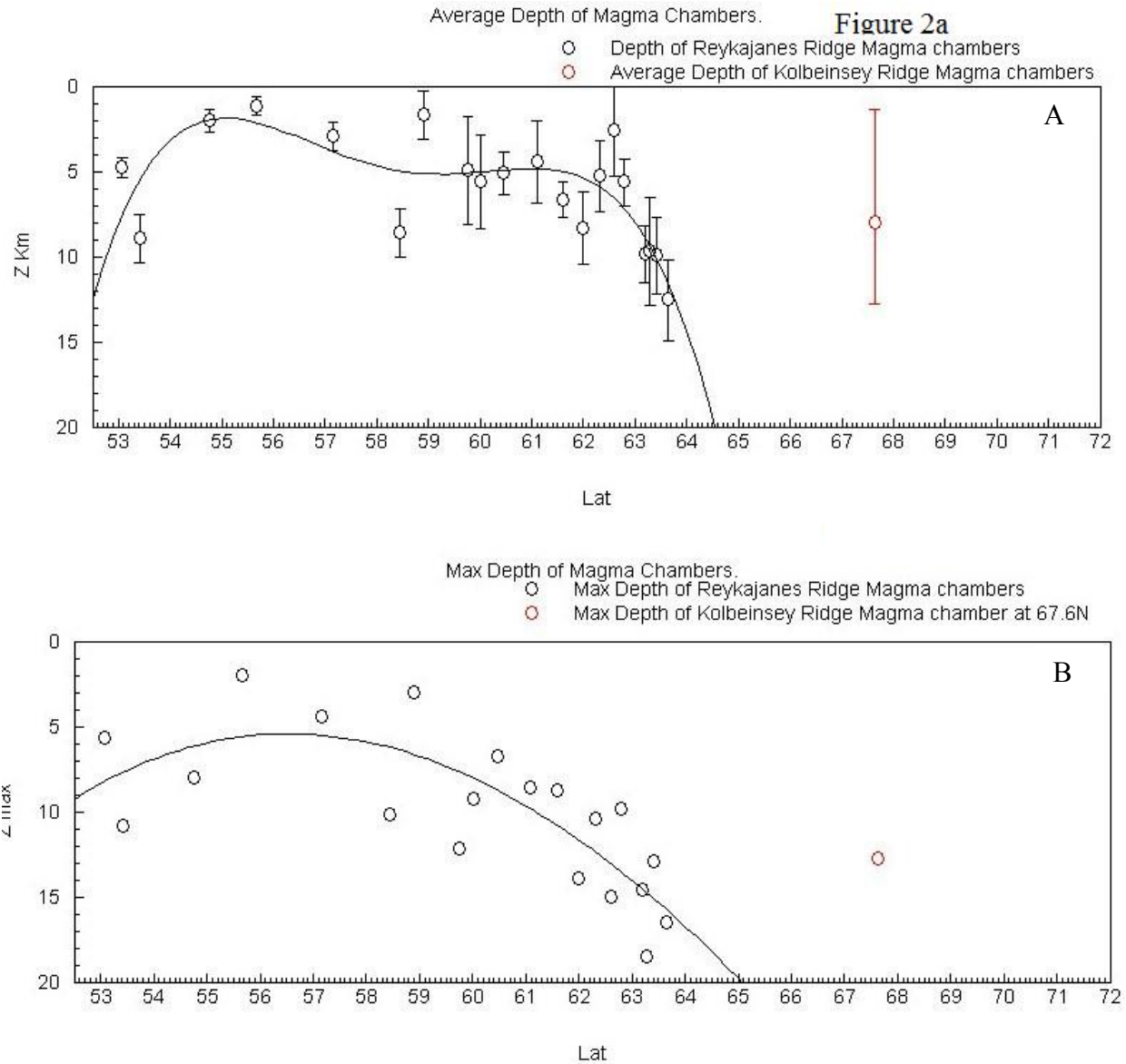


Figure 6: The Reykjanes ridge is between 53° to 64° N. Iceland is between 64° and 66° N and the Kolbeinsey Ridge is between 66° and 72° N. The average depth for each magma chamber bracketed by one standard derivation for uncertainty. The maximum depths are associated with the bottom of the crust.

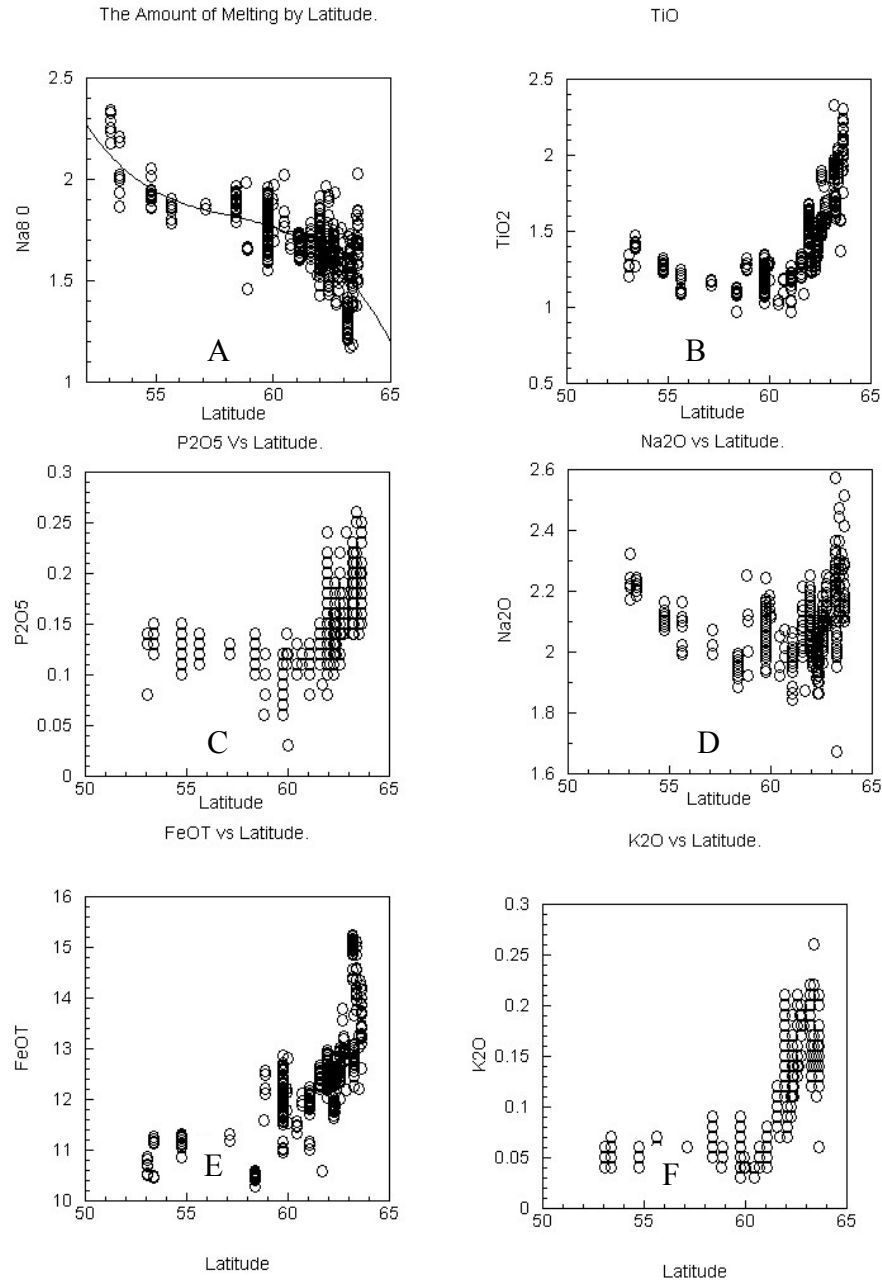


Figure 7: Graph A – Na₈O concentration as a function of latitude (approaching Iceland from the south) the decrease in Na₈O show a increase in melt. Graph B-F – Trends in incompatible elements as Iceland is approached from the south. Note that as Iceland is approached, incompatible element concentrations increase. This trend would not be expected from a uniform magma composition beneath the length of the ridge.

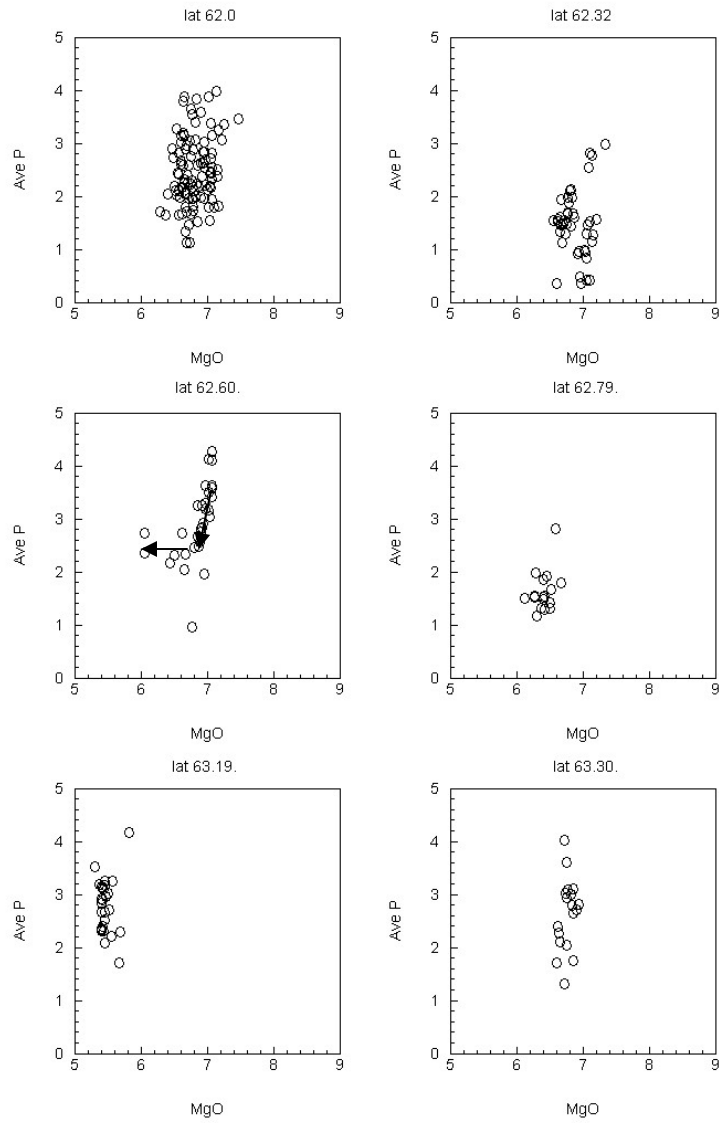


Figure 8: pressure vs. MgO for location 62.0-63.19. The graph do not show a clear pressure for a magma chamber supporting the many sills model.

References

- Christie, David M; Carmichael, Ian S E; Langmuir, C H, Oxidation States of Mid-Ocean-Ridge Basalt Glasses. *Earth Planetary Science Letters* v.79 (1986) p.397-411
- Cohen, R. S.; Evensen, N. M.; Hamilton, P. J.; O'Nions, R. K. U-Pb, Sm-Nd and Rb-Sr systematics of mid-ocean ridge basalt glasses *Nature (London)*. v. 283 no. 5743 (1980) p. 149-153
- Devey, C. W., et al. "Geochemical Effects of Dynamic Melting beneath Ridges - Reconciling Major and Trace-Element Variations in Kolbeinsey (and Global) Midocean Ridge Basalt." *Journal of Geophysical Research-Solid Earth* 99 B5 (1994): 9077-95.
- Foulger, G. R.; Anderson, D. L. A cool model for the Iceland hotspot *Journal of Volcanology and Geothermal Research*. v. 141 no. 1-2 (2005) p. 1-22
- Grove, T. L., Gerlach, D. C., Sando, T. W. & Baker, M. B. Origin of calc-alkaline series lavas at medicine lake volcano by fractionation, assimilation and mixing corrections and clarifications(vol 82, pg 407, 1983). *Contributions to Mineralogy and Petrology* v. 114, (1993). 422-424.
- Hermes, O. D.; Schilling, J.-G. Olivine from Reykjanes Ridge and Iceland tholeiites, and its significance to the two-mantle source model *Earth and Planetary Science Letters*. v. 28 no. 3 (1976) p. 345-355
- Herzberg, C. "Partial Crystallization of Mid-Ocean Ridge Basalts in the Crust and Mantle." *Journal of Petrology* 45 12 (2004): 2389-405. Hilton, D. R.; Murton, B. J.; Nichols, A.; Taylor, R. N.; Thirlwall, M. F. Controls on magmatic degassing along the Reykjanes Ridge with implications for the helium paradox *Earth and Planetary Science Letters*. v. 183 no. 1-2 (2000) p. 43-50
- Kelley, D. F.; Barton M. Pressures of Crystallization of Icelandic Magmas *Journal of Petrology*.

v. 49 no. 3 (2008) p.465-492

Kyser, T. Kurtis; O'Neil, James R. Hydrogen isotope systematics of submarine basalts

Geochimica et Cosmochimica Acta. v. 48 no. 10 (1984) p. 2123-2133

Langmuir, C. H., E. M. Klein, and T. Plank Petrological Systematics of Mid-Ocean Ridge

Basalts: Constraints on Melt Generation Beneath Ocean Ridges, *AGU Monograph*, 71, (1992) p.183-2

MacLennan, J., T. Hulme, and S. C. Singh. "Thermal Models of Oceanic Crustal Accretion: Linking

Geophysical, Geological and Petrological Observations." *Geochemistry Geophysics Geosystems* 5 (2004):
32.

Melson, W G; O'Hearn, T, Smithsonian Volcanic Glass File

Meyer, P. S., Schilling, J. & Sigurdsson, H Petrological and geochemical variations along

Iceland's neovolcanic zones. *Journal of Geophysical Research*, B v. 90, (1985). p.10043-10072.

Michael, P. Regionally Distinctive Sources of Depleted MORB - Evidence from Trace-Elements

and H₂O. *Earth and Planetary Science Letters*, v.131 (1995) p.301-320.

Michael, P. J., and W. C. Cornell. "Influence of Spreading Rate and Magma Supply on

Crystallization and Assimilation beneath Mid-Ocean Ridges: Evidence from Chlorine and Major Element
Chemistry of Mid-Ocean Ridge Basalts." *Journal of Geophysical Research-Solid Earth* 103 B8 (1998):
18325-56.

Murton, B. J., Taylor, R. N. & Thirlwall, M. F. Plume-ridge interaction: A geochemical

perspective from the Reykjanes Ridge. *Journal of Petrology*, v. 43 (2002) p.1987-2012.

Pan, Y. C., and R. Batiza. "Magmatic Processes under Mid-Ocean Ridges: A Detailed

Mineralogic Study of Lavas from East Pacific Rise 9 Degrees 30 ' N, 10 Degrees 30 ' N, and 11

- Degrees 20 ' N." *Geochemistry Geophysics Geosystems* 4 (2003): 33.
- Pan, Y. C., and R. Batiza. "Mid-Ocean Ridge Magma Chamber Processes: Constraints from Olivine Zonation in Lavas from the East Pacific Rise at 9 Degrees 30 ' N and 10 Degrees 30 ' N." *Journal of Geophysical Research-Solid Earth* 107 B1 (2002): 13.
- Poreda, R.; Craig, H.; Schilling, J. G. Helium and hydrogen isotopes in ocean-ridge basalts north and south of Iceland *Earth and Planetary Science Letters*. v. 78 no. 1 (1986) p. 1-17
- Ryan, Jeffrey G.; Langmuir, Charles H. The systematics of lithium abundances in young volcanic rocks *Geochimica et Cosmochimica Acta*. v. 51 no. 6 (1987) p. 1727-1741
- Schiellerup, H. Generation and equilibration of olivine tholeiites in the northern rift zone of Iceland; a petrogenetic study of the Blafjall table mountain. *Journal of Volcanology and Geothermal Research* v.65 (1995). p.161-179.
- Sigurdsson, H, First-order Major Element Variation in Basalt Glasses From The Mid-Atlantic Ridge: 29 Degree N TO 73 Degree N, *Journal of Geophysics Research* v 86 (1981) p. 9483-9502
- Walker, D., DeLong, S. E. & Shibata, T. Abyssal tholeiites from the Oceanographer fracture zone; II, Phase equilibria and mixing. *Contributions to Mineralogy and Petrology* v.70 (1979). p. 111-125.
- van Wijk, J. W., and D. K. Blackman. "Development of En Echelon Magmatic Segments Along Oblique Spreading Ridges." *Geology* 35 7 (2007): 599-602.
- Wood, D. A.; Bizouard, H.; Bougault, H.; Cann, J. R.; Corre, O.; Duffield, W. A.; Faller, A. M.; Hawkesworth, C. J.; Joron, J. L.; Kobayashi, K.; Norry, M. J.; Poore, R. Z.; Roberts, W. P.; Roddick, J. C.; Shambach, J. D., editor; Sharman, G.; Shor, A. N.; Steiner, M.; Steinmetz, J. C.; Treuil, M.; Varet, J.; Varet, J.; Vennum, W.; Wood, D. A.; Zolotarev, B. P. The petrology, geochemistry, and mineralogy of North Atlantic basalts; a discussion based on IPOD Leg 49 Initial Reports of the Deep Sea Drilling Project. v. 49 (1979) p. 597-655

Yang, H. J., Grove, T. L. & Kinzler, R. J. Experiments and models of anhydrous, basaltic

olivine[^]plagioclase[^]augite saturated melts from 0.001 to 10 kbar. *Contributions to Mineralogy and Petrology* v. 124 (1996). p. 1-18.

www.petdb.org